Chapter 3
Radiography

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Abstract Radiography evolved from laboratory testing into in-situ applicable methods that utilize low-energy gamma X-ray sources. Due to the low attenuation properties of wood and difference in attenuation of different material, the radiography is relatively easily applicable to timber. Parameters such as energy level, time of exposure and distance between the source, object and imaging plate permit identification of early and late wood. Quantitative radiography can be used to extract dimensions, deformations or even strains. One of the challenges is the collapse of a three dimensional object into two dimensions. Access must available from opposite sites of the member.

Key words: X-ray, gamma rays, quantitative radiography, radioscopy, attenuation, relative attenuation, sharpness, source, digital imaging, wavelength, spectrum, cracks

3.1 Background

Radiography uses penetrating radiation to depict the internal structure of members. A radiation source is used to emit a beam of radiation directed towards an object of interest. Objects under investigation will have varying absorption of radiation based on the material density and thicknesses. Opposite the source of radiation and behind the object of interest is a radiation sensitive film or recording medium that produces images (see Figure 3.1). This noninvasive procedure allows for extensive investigation into issues such as structure composition, hidden internal materials and flaws and the state of preservation, which at times cannot be gained by other means.

Digital imaging systems and digital radioscopy have seen advancement because of their traditional use in security, bomb and drug detection, and forensics as well as industrial non-destructive testing for quality assurance. The advancement seen from these commercial uses have lead to the development of highly portable and user

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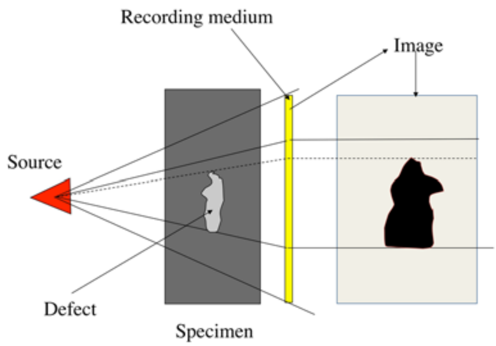

Fig. 3.1 General arrangement for radiographic imaging

friendly systems that can be run either on battery or with common AC/DC adaptors depending on the system. Laptop computers are generally used with these systems and allow for nearly instant image viewing and manipulation. Such advancements have led the technology to be readily applied to in situ investigations.

3.2 Equipment

3.2.1 Technology

Penetrating radiation used in radiography is generated from several sources, most commonly electrons, neutrons, gamma rays and X-rays. Electrons used in radiography are produced either by radioactive decay or high-energy X-ray impact on a heavy metal. Because of the strong absorption of electrons by all materials, the penetration power is limited and restricts the usefulness of this radiation source to thin, low density material [1].

Neutrons are produced by linear accelerators or nuclear reactors and are prone to absorption by organic material. Neutrons are rarely used for in situ investigation for multiple reasons including the limited access to linear accelerators or nuclear reactor sources, the expense of equipment and operation, issues related to the difficulty of on-site equipment set up, limitation to small areas of investigation due to the narrowness of the radiation beam produced, poor reaction of neutrons with film, and the possibility of objects becoming radioactive after investigation [1]. These drawbacks limit the use of electron and neutrons as radiation sources for in situ investigation and the remainder of the discussion will focus on gamma and X-ray radiation sources.

Gamma rays and X-rays are the most commonly used sources of radiation used for radiography. They are short wavelength electromagnetic radiations which are physically the same but differ in the way they are produced. Both travel in straight

lines at the speed of light, can be diffracted but not deflected, and are unaffected by electrical or magnetic fields. The rays penetrate matter, the degree of which is dependent on material type, density and thickness as well as the radiation energy [1,2].

3.2.2 Gamma Rays

Gamma rays are emitted during the radioactive decay of unstable isotopes, each having a characteristic energy and intensity for the radiation it emits. The high energy levels of the gamma rays create substantial penetration capabilities. Isotope energy remains constant; however, the intensity decays with time as indicated by the half life. The wavelengths of the radiation produced by the gamma sources are distinct and limited as opposed to X-rays which have a broad wavelength spectrum.

Although gamma and X-rays are physically the same, the production differences have a distinct effect on gamma rays use for in situ evaluation. Gamma rays have the advantage of a portable nature since radioactive isotopes do not require the external energy or cooling sources that X-ray generators do. The elimination of external power, as well as the reduction and compactness of the equipment, make the method more mobile and less expensive.

The advantages of a radiation source with no external power are limited. The radioactive isotopes continually generate radiation and require special containers lined with lead for storage to protect against the harmful effects of the radiation on living tissue. In addition, when use of the source is needed it must be removed from the storage container by means of a remote controlled mechanical device. The source also has a limited life span as it loses its intensity over time, depending on the half-life of the isotope in use, and the high energy radiation of gamma rays cannot be controlled, resulting in poorer quality imaging with lower contrast than X-rays [1].

3.2.3 X-Rays

X-rays are produced when high-speed electrons impact matter. Energy is lost upon impact and a small fraction is converted into short wavelength radiation. The remaining impact energy is mostly converted to heat. The X-ray spectrum is comprised of two underlying spectrums, the line spectra and the continuous or "white" spectra. The line spectrum is specific to the material under investigation and has specific wavelengths. The continuous spectrum is the one used in radiography and is produced by the rapid deceleration of the electrons on impact and has a broad range of wavelengths [3]. Wavelength and energy are used to characterize X-rays and are related through the equation below where E is the radiation energy, h is Plank's constant, c is the velocity of light and λ is the radiation wavelength. From inspection, higher energy will have shorter wavelengths, allowing for more penetration

capability.

$$E = \frac{hc}{\lambda} = \frac{1.24}{\lambda} \tag{3.1}$$

X-ray tubes are a key component in the generation of X-rays beams for traditional X-radiography. A cathode and an anode are contained within a glass bulb under vacuum. The cathode contains a wire filament which will emit a continuous stream of electrons when heated to incandescence. The anode contains a target at which the electrons are directed. It is at this target that X-rays are produced upon impact. This target is generally made of tungsten for two reasons, first, it is a good source of high-energy X-rays and second, it has a high melting point. Most of the energy used for X-ray production (99%) is converted to heat and most of this heat conversion takes place at the target so it is necessary to have target material which can withstand high temperatures.

The electrical tension between the anode and cathode causes the acceleration of the electrons to the target, and the electron stream is focused into a beam by a cylinder or focusing cup. After impact on the target, the X-rays exit through a window made of a light element, usually beryllium, that will not absorb much of the radiation as it passes. The target is oriented at an angle to the beam of electrons in order to project the X-rays out the window. The angle at which the target is oriented reduces the effective width of the target and the X-ray beam width. This will have a large effect on the image production as a smaller effective target width produces sharper radiographs.

X-ray equipment is characterized by its potential (in volts) and current; factors which control the intensity and penetration capabilities of the radiation. Typical equipment has a range from 50 up to 320 kV; equipment designed for specialized uses may range up to 450 kV. For portable units a potential of 200 kV with intensity of 3 mA is standard [1, 2].

3.2.4 Radiation Attenuation

As X-rays and gamma rays pass through material, attenuation occurs depending on the material composition, density and thickness as well as the energy of the radiation beam. This attenuation, or loss in intensity, is what makes radiographic inspection possible. The detection of the difference in radiation intensity is recorded to produce radiographic images that allow for detailed assessment. The intensity of radiation upon exit of a material is given by

$$I_X = I_O \cdot e^{-\mu \cdot t} \tag{3.2}$$

where I_X is the emergent intensity, I_O is the initial intensity, t is the thickness of the material and μ is the linear absorption coefficient per unit thickness, a material characteristic affected by the density. The absorption coefficient is frequently reported

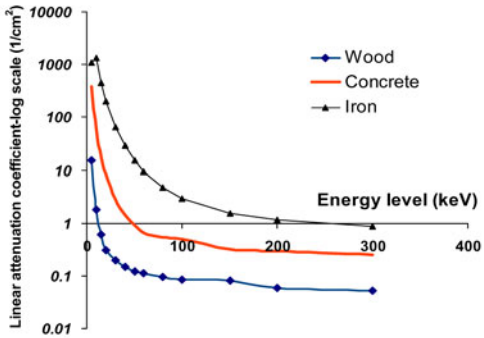

Fig. 3.2 Linear attenuation (absorption) coefficient (μ) for wood, concrete and steel [4] as a function of energy level

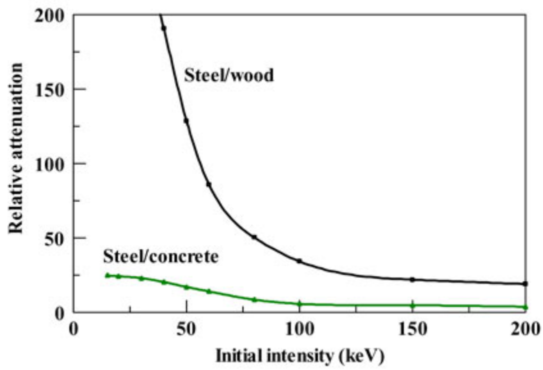

Fig. 3.3 Relative attenuation for steel, concrete and wood

as a mass absorption coefficient in which the linear absorption coefficient is divided by mass density.

Relative attenuation (composition contrast) is important along with the radiation intensity leaving the object. The relative attenuation is a function of the energy level and decreases as the energy level increases. This creates potential difficulties in materials with similar attenuation values or when a medium has a relatively high attenuation such as reinforced concrete. This problem is illustrated in Figure 3.3. The largest differential attenuation is at low energy levels but such levels may not penetrate the investigate material as it is frequently the case in reinforced concrete. Increasing the input energy levels will decrease the relative attenuation and the resulting sensitivity. The chart in Figure 3.3 is normalized assuming unit thickness. For example at 50 keV the ratio between steel and wood thickness will have to reach about 150 for the attenuation to be equal while at 200 keV level the ratio will drop to about 25.

Composition contrast is affected by the x-ray wavelength and wavelength versus mass absorption charts can be used to find the optimum wavelength. The relation-

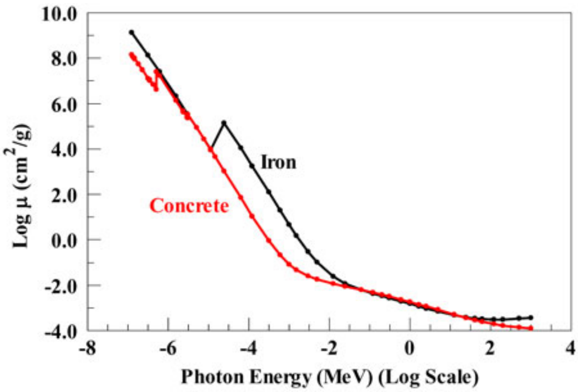

Fig. 3.4 Photon energy versus mass absorption coefficient for iron and concrete [4]

ships between mass absorption and the wavelength or mass absorption and photon energy experience discontinuities depending upon the mechanism controlling the attenuation (Thompson (coherent) scattering, photoelectric effect, Compton (incoherent) scattering, pair-production of an electron and positron, and photodisintegration). At different energy level, different mechanism may prevail and this results in discontinuities in energy-mass absorption curves (Figure 3.4).

From Figure 3.4 it is clear that at certain energy levels mass absorption coefficients of iron and concrete will be almost equal. Composition contrast will be at a minimum at x-ray energies of about 1 MeV where the mass absorption coefficients will be about the same for all materials [5]. Real-time radiography is gaining acceptance in laboratory investigations where the image is digitized via a convertor and displayed and stored at the same time [5]. Imagers with acquisitions speeds exceeding 20 frames per second (fps) are available and the acquisition rates will further increase. The acquisition rate is linked with the image quality and higher rates result in lower pixel density. The real-time radiography offers a unique opportunity to investigate transient processes both quantitatively and qualitatively [5]. While currently confined to a laboratory environment, the-situ applications are a logical extension of this technique.

Attenuation is also dependent on the radiation energies. Radiation with low energies are more readily absorbed and prone to scatter, resulting in less penetrative power. In contrast, higher energy beams will be more penetrative with less absorption and subsequent scatter.

3.2.5 Imaging

Radiographic images are produced based on the intensity of radiation exposure on an imaging plane. Images can be permanently recorded using traditional film or

paper mediums, or sensitive real-time imaging mediums integrated with digital systems and software.

Film radiographs are the traditional form of capturing images. These films have an emulsion that reacts and changes when exposed to radiation. Upon development, a negative image or “shadow image” is produced where denser areas, which allow less radiation exposure, appear lighter. This form of imaging has been limited for in situ evaluation when used with the traditional high-energy radiations for safety concerns as well as the high cost of the operation; however it does provide a permanent record of the investigation and film is relatively inexpensive to purchase and process.

Radioscopy, or real time imaging, was one of the first forms of radiographic imaging. Traditionally florescent screens were used with high-energy radiation sources to produce an image based on the ensuing radiation. The screen emitted light based on the radiation it was exposed to; brightness being proportional to the intensity of the ensuing radiation, producing a positive image. This method was more portable than film radiographs and offered the advantage of real-time images that could be utilized to improve the inspection. There was however safely concerns associated with the high-energy radiation source and such a technique was unable to record the images for future analysis.

With technological advances digital radioscopy has emerged as a viable assessment option without previous drawbacks. The radiation source can be of a lower energy and detected radiation can be recorded on reusable imaging screens and processed into digital images that can be stored for future use. The digital storage of images allows for powerful image enhancing tools to be utilized which can provide more detail and allow for further information extraction.

3.2.5.1 Image Quality

High contrast and sharpness are desired and make inspection and interpretation of the radiographs easier. Geometric features relating to equipment and object positioning will affect the image sharpness. The image property known as geometric unsharpness, U_g, is given by an equation with variables S denoting the size of the focal spot within an X-ray tube, a denoting the distance from the source to the object, and b denoting the distance from the object to the imaging material.

$$U_g = S\left(\frac{b}{a}\right) \tag{3.3}$$

Sharpness and image quality will decrease if the focal spot in the radiation equipment is large and with the increase in distance between the object and recording medium. Distance between the object and the recording medium should be kept at a minimum to improve image quality and to avoid image magnification and distortion. The distance b can be increased to produce a magnification of the object to inspect small features, but this should be done carefully to keep the unsharpness at an ac-

ceptable level [1]. The contrast of images is the amount of difference seen between densities and is an important quality issue since good contrasts distinguishes member features. Contrast of radiographic images is highly dependent on the recording material and energy levels of radiation. Lower energy radiation produces higher quality contrasts, but is limited in its penetration ability and the range of densities it can produce on an image. Higher energy levels, while more penetrative, will have less contrast in images. Selection of radiation energy will most likely depend on the material investigated as well as the detail needed in the radiographs.

Image quality can be greatly affected by the selected view (the source, object, imaging plate relation). In general it is best to orient the radiation source and the image capturing material at right angles to the object surface to avoid gross distortions which make interpretation difficult. This however is not always plausible or desired based on the in situ member orientation and shape, the available access, or specific areas of interest on the object that do not lend themselves to this type of arrangement. This can cause increased difficulty in radiograph interpretations as a result of distorted size, orientation or overlapping images. It is helpful to place identifying markers on the imaging planes as a reference point to help identify the proper orientation of the image. This is true not only in cases where interpretation is suspected to be difficult, and it makes future interpretations of the images easier if the marker orientation is known or standardized. These markers should be of a material that will easily appear on the radiograph and should be placed on the outer edge of the imaging planes to avoid interfering with the area of interest.

Orientation of the radiation beam must also be carefully considered for deterioration or crack detection. It must also be noted that for crack detection, the radiation beam must be parallel to the crack or the crack must be sufficiently large to be detected.

3.2.5.2 Image Enhancement

Digital imaging systems offer the ability for image enhancement. Laptop computers can process the images onsite many times and perform numerous manipulations to improve image clarity. Manipulations would include contrast adjustments, brightness, color processing, figure orientation and magnifications. A feature useful for image interpretation reverses the gray scale so that darker areas will correspond with areas of higher density, producing a more intuitive represented image of the member. Software can also produce grid overlays and measure image features on screen. On-site imaging and enhancement also gives inspectors the advantage of viewing their work to make further images and adjustments as necessary for their needs.

3.3 Application

Radiography has been used since the 1960s for defect and deterioration detection investigations of in situ structures. Original use of high energy X-ray sources limited radiographic investigation, but the development of digital radioscopy systems has increased its use due to reduced safety concerns and cost, the ability to produce images nearly in real time with reusable imaging plates, and the capability to perform initial image assessment and manipulation on site [6]. Application on notable structures includes Thomas Jefferson's Academicals Village at the University of Virginia, Monticello, and the Narbonne house in Salem Massachusetts. Radiographic images were used to investigate the timber condition as well as verify the existence and condition of metal fasteners and hardware and answer questions of internal or hidden construction techniques [6, 7]. For this application, the interest lies in X-ray use to locate deterioration in timber members and discussion will be limited to that topic.

Attenuation is a function of the radiation energy, member thickness and, important for material condition inspection, density. Timber condition can be assessed by examining the density variations of radiographic images. Decay will appear as areas with less density resulting from the breakdown of the material.

Stages of deterioration can be identified through the examination of the radiographs. Sound wood will present a clearly defined wood structure including annular rings or grain, and optical density will be uniform. Partial decay will show loss in the wood structure, annular rings will appear but will be vague, and the optical density will vary over the material showing areas of density deviation. Decayed areas will have lost the wood structure, appearing only as an amorphous mass. Horizontal separation lines will appear resulting from the material breakdown, and decay pockets will be identifiable. Advanced decay will have the same features, but they will be more severe and extended through the member [8].

High resolution images of wood members can be produced which will show density variations between early wood and late wood. This distinction in density variation allows for grain to be visible in the images, as shown in Figure 3.5. Variations or loss in grain distinction can be used to assess timber construction as well as identify areas where deterioration or infestation has set in. Figure 3.6 shows an example of a deteriorated member; the lighter portions of the image correspond to loss in density due to decay, the grain pattern in lost in this area as well.

Disruption in grain structure can be used to locate internal features such as knots and grain deviations. Insect damage has been identified and located using radiography on timber members. Mechanical damages, such as fractures, drill holes, cuts, or naturally occurring cavities can also be identified.

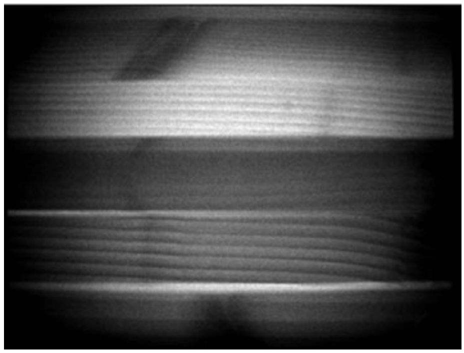

Fig. 3.5 Example of sound wood with wood grain visible in X-ray image, gluelam beam

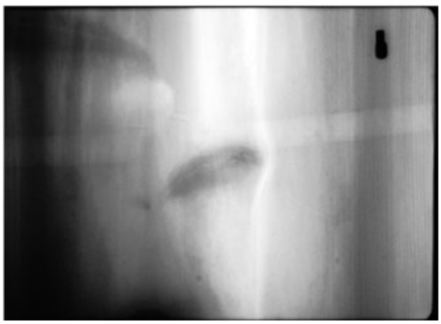

Fig. 3.6 Example of deterioration visible in X-ray image

3.4 Limitations

While radiography offers the ability to view internal characteristics of members, there are limitations and disadvantages to the technique. Radiographic investigation can commonly identify deterioration and defects in timber material; however defect depth can be hard to establish, and the extent of deterioration cannot be quantified. Radiographic images produce a two dimension representation of the inspected timber member by compressing data through the thickness into one plane. Therefore the density data and images produced represent the average density of the member through the thickness. This fundamental imaging process does not allow for information to be gathered on the depth of internal features and can make detection of cracks or defects that are oriented perpendicular to the radiation path difficult. This also makes estimates on the amount of material lost to degradation and decay difficult based on single images of the member. Sound wood structure can also be superimposed over deteriorated areas and make interpretation and quantification difficult.

More images, taken from different angles and on different faces, would help in gaining perspective on the extent of internal damage. This would raise the time

and cost associated with the investigations. Research into the ability to quantify deterioration through image manipulation and radiographic data is, however, being investigated currently.

Detection of internal flaws using radiography can be limited by size and orientation of defects. Locating internal cracks requires that the crack be of adequate size, at least 2% of the member thickness [2], and must be oriented parallel to the radiation beam to be detected.

Although reduced with the development of low energy portable X-ray systems, safety can be a concern which can limit its use. Radiation is not detectable to human senses but it is very harmful to living tissue. With these characteristics, it is important to monitor radiation exposure when using radiography. This is especially true when using high energy sources needed for inspecting high density or thick members. Safety risks can be minimized by monitoring exposure and using good protective practices with radiation. Exposure is most commonly monitored using pocket dosimeters or film badges worn by personnel at investigation sites. The level of exposure can be controlled by simple means. Restrictions should be placed on the source intensity and the emission direction and all persons in the area should be kept informed as to when exposures are done as well as kept out of the immediate area of radiation investigation [2].

Limitation on the intensity or energy level of the radiation source can also limit investigation of materials. Thick members may be difficult to examine with the low energy radiation sources that are used for in situ investigations. If the member is too thick not enough X-rays will be transmitted to produce quality images, or the time required to scan with adequate results will be excessively long [9].

Member arrangement can also make positioning of the source and imaging plates very difficult and require equipment solely for access purposes, as well as more thought and time put into the set up and interpretation of the images. Problems placing image capturing materials opposite radiation sources can arise in many situations. Most equipment currently used for radiographic investigation requires access to opposing sides of a member, which for in situ testing may not be available. View choice may also be obstructed by other structural material making the desired view of the member inaccessible.

In addition to these functional issues, radiography is also a more expensive form of nondestructive testing than many other alternative methods. Portable units make members more accessible for inspection, and allow for processing the images onsite with little to no costs, but the initial costs of the equipment can be prohibitive. Limitations on source energy will also increase time needed and costs incurred with inspection of thick or very dense members.

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